



<b>Title</b>	<b>On wavelength-routed networks with reversible wavelength channels</b>
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<b>Citation</b>	<b>IEEE Journal of Lightwave Technology, 2013, v. 31, p. 1409-1417</b>
<b>Issued Date</b>	<b>2013</b>
<b>URL</b>	<b><a href="http://hdl.handle.net/10722/191336">http://hdl.handle.net/10722/191336</a></b>
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# On Wavelength-Routed Networks With Reversible Wavelength Channels

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**Abstract**—We observe that the performance of wavelength-routed (WR) networks often suffers from asymmetric traffic and network traffic patterns differing from the original design plans. WR networks with a fixed number of channels in a given transmission direction are inflexible. Therefore, we propose reversible wavelength channels. Like a reversible lane in highway systems, a reversible wavelength channel has the flexibility of its transmission direction being configurable at the setup of a lightpath. So far reversible wavelength channels have not been discussed in WR networks even though we observe that most of the required technologies are already available. In this paper, we discuss all the required technologies for implementing reversible wavelength channels in WR networks. We demonstrate that reversible wavelength channel can provide significant performance improvement for WR networks when the traffic is asymmetric. Even if the traffic is symmetric, we also have nontrivial performance improvement with reversible wavelength channels, i.e., the blocking performance of WR networks with reversible wavelength channels will be similar to that of normal WR networks with doubling the number of fibers per link. Different implementation approaches for reversible wavelength channels are discussed. Among them, the performance of the reversible waveband approach is discussed in detail.

**Index Terms**—Lightpath, reversible waveband, reversible wavelength channel, wavelength-routed networks.

## I. INTRODUCTION

WAVELENGTH-ROUTED (WR) networks are one of the important networking infrastructures to provide the required transmission bandwidth for the rapidly increasing Internet traffics [1], [2]. In WR networks, wavelength division multiplexing (WDM) divides the transmission bandwidth of optical fiber into hundreds of wavelength channels. Two users desiring communication can set up a lightpath connection by simply reserving a wavelength channel on each fiber link of the path between them [3], [4]. Traditionally, all wavelength channels have been allocated the same amount of bandwidth for

simplifying and standardizing the implementation and deployment, e.g., the 100 GHz frequency (0.8 nm wavelength) spacing in ITU grid [5]. As transmission technologies advance, wavelength channels will often be under-utilized, i.e., channels are over-provisioned for normal user traffics. To have a better bandwidth utilization, efforts have been made on packing more low data rate traffics into a wavelength channel [6], using smaller channel spacing such as 50 and 25 GHz [5], and more recently, using the variable bandwidth allocation of wavelength channels [7]. While the importance of properly matching channel bandwidth to user's demand has been widely recognized, the mismatch between the ratio of the capacities (numbers of channels) deployed in the two transmission directions of a fiber link has been overlooked.

In most deployed networking infrastructures, the links connecting two nodes are often assigned the same number of channels in both transmission directions. The assumption is that the volumes of traffics in both transmission directions of a link are often nearly equal. In the real world, however, traffics between users are often not necessarily symmetric [8]–[10], not to mention the frequent changes of traffic patterns in today's networks. As the Internet becomes an important resource to provide information and entertainment [10], we are facing networks with increasingly dynamic traffic patterns.

If we treat optical fibers as roads, the wavelength channels may be considered as lanes. In highway systems, reversible lanes have already been widely regarded as one of the most cost-effective methods to provide additional capacity for periodic unbalanced directional traffic demand while minimizing the total number of lanes on a roadway [11]. Undoubtedly, the negative impact of asymmetric traffic distribution will be mitigated in WR networks if the transmission directions of all wavelength channels can be freely reversed according to the traffic condition, i.e., with reversible wavelength channels. Proposals to accommodate wavelength channels with different transmission directions into a single fiber similar to that of roads have been made, e.g., passive optical networks and single fiber bidirectional rings [13]–[15]. However, these proposals are mainly for reducing the deployment and operation costs of optical fiber networks. The performance benefits of reversible wavelength channels have been neglected, even though most of the required technologies such as bidirectional couplers [16], [17], bidirectional add-drop multiplexers [18]–[21], bidirectional optical amplification [22]–[30], and bidirectional optical switches [31]–[35] are already available. As more flexible bandwidth utilization is desired in today's networks, we propose reversible wavelength channels to be used in WR networks.

In Section II of this paper, we will first introduce the architecture of the proposed WR networks with reversible

Manuscript received February 17, 2012; revised November 30, 2012; accepted February 22, 2013. Date of publication March 07, 2013; date of current version March 15, 2013. This research was supported in part by a grant from the Hong Kong Polytechnic University (Project Number J-BB9M), and in part by the University of Hong Kong Strategic Research Theme of Information Technology.

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Digital Object Identifier 10.1109/JLT.2013.2250481

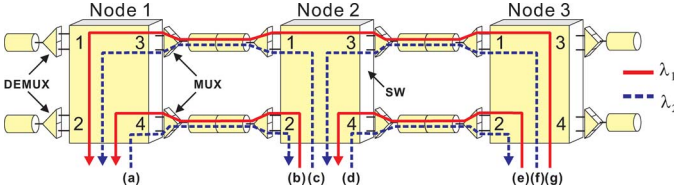


Fig. 1. Three nodes of a WR network with reversible wavelength channels.

wavelength channels. We will also give a review of the available technologies that are important for the implementation. In Section III, we demonstrate the performance improvement of WR networks under different traffic distributions if reversible wavelength channels are used. Simulations show that reversible wavelength channels can significantly improve WR network performance even if the traffic patterns are not asymmetric, i.e., the blocking performance of WR networks with reversible wavelength channels will be similar to that of normal WR networks with doubling the number of fibers per link. Then, we discuss different implementation considerations for the reversible wavelength channels in Section IV. We conclude in Section V.

## II. WR NETWORKS WITH REVERSIBLE WAVELENGTH CHANNELS

### A. Principle and System Requirements

Fig. 1 shows three nodes (labeled with 1, 2 and 3) of a WR network with reversible wavelength channels. A node is simply represented by a combination of wavelength multiplexers (MUX), demultiplexers (DEMUX) and optical switch (SW). In Fig. 1, each node has four fibers connected to its adjacent nodes and there are two wavelength channels ( $\lambda_1$  and  $\lambda_2$ ) per fiber, i.e., Ports 1 and 2 of a node are connected to Ports 3 and 4 of its adjacent node in the figure. Assuming that the required data transmission bandwidth between nodes in units of wavelength channels (also shown in Table I) are (1) Node 1 receives two units from Node 2 and one unit from Node 3, (2) Node 2 receives one unit from Node 1 and two unit from Node 3, and (3) Node 3 receives one unit from Node 2. This requires us to allocate three wavelength channels connecting from Node 3 to Node 2 and another three from Node 2 to Node 1. Also, we need one wavelength channel connecting from Node 1 to Node 2 and another one from Node 2 to Node 3. If this is a traditional WR network, there will be a problem to set up lightpaths to meet such bandwidth requirement. Traditional WR networks only have non-reversible wavelength channels with fixed transmission direction. Most likely, the two fibers connecting two nodes are with opposite transmission directions. It will be not possible to set up the lightpaths within the three nodes in traditional WR networks. We will need to block some of the transmission requests. On the other hand, we may set up lightpaths (a) to (g) as shown in Fig. 1 if wavelength channels are reversible. The wavelength channels in the upper two fibers of Fig. 1 are configured with transmission direction from right to left. Those in the lower two fibers are configured

TABLE I  
REQUIRED TRANSMISSION BANDWIDTH BETWEEN  
NODES IN WAVELENGTH CHANNELS

destination source	Node 1	Node 2	Node 3
Node 1	0	1	0
Node 2	2	0	1
Node 3	1	2	0

with Channel  $\lambda_1$  to left and Channel  $\lambda_2$  to right, i.e., the lower two fibers in Fig. 1 are bidirectional transmission fibers.

Reversible wavelength channels allow the flexibility to fully utilize the deployed optical fiber network infrastructures to lessen the need for new fiber infrastructure deployments even if the traffic becomes dynamic, or if the traffic patterns have deviated greatly from the original design plans. Note that fiber infrastructures are one of the major investments in optical fiber communication networks. As shown in Fig. 1, however, reversible wavelength channels will require WR network devices to be bidirectional and reconfigurable.

First of all, each wavelength channel on a fiber should be reconfigurable to support data transmission in either direction. Note that a reversible wavelength channel, like a reversible lane in a highway system, can have transmission in only one direction at any moment but with flexibility of the direction being configurable at the setup of a lightpath. We do not consider the case of transmissions in two channels with the same wavelength but different directions because it is possible with short distance fiber links only [36]. As wavelength multiplexers and demultiplexers are in general passive devices and bidirectional, a fiber without isolator to limit the optical signal reflection can be considered as a bidirectional link. Recently, bidirectional isolators have also been proposed to improve the transmission performance of bidirectional fiber links [16], [17], i.e., a single fiber with channels in different directions. Reversible wavelength channels will need the bidirectional isolators to be reconfigurable and the required technologies have already been demonstrated in other devices such as bidirectional add-drop multiplexers [18]–[21].

Reversible wavelength channels will need optical amplification if the distance between nodes is long. Commercially available optical amplifiers for long distance transmissions are not bidirectional. There have been many proposals for optical amplification of bidirectional fiber links including repeaterless approaches – pre and post amplifying the optical signals at transmitters and receivers, respectively, instead of adding a bidirectional optical amplifier at the middle of the transmission path [22]–[25], and repeated approaches – adding bidirectional optical amplifiers in the path [26]–[30]. Surely, using bidirectional optical amplifiers will allow the networks to have a larger coverage. Among the proposed bidirectional optical amplifiers, the co-propagating amplifier architecture [29], [30] is suggested as the building block for the required reconfigurable bidirectional optical amplifiers as shown in Fig. 2. This is because commercially available high performance erbium doped fiber amplifiers (EDFAs) optimized for low noise figure and high output power are fundamentally unidirectional devices. Also, the performance of co-propagating architecture bidirectional

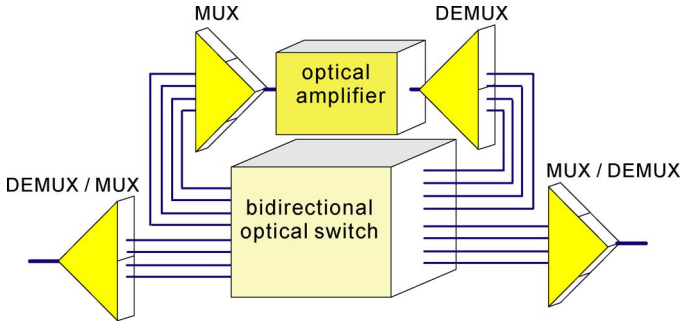


Fig. 2. A reconfigurable bidirectional optical amplifier.

amplifiers has been demonstrated in both laboratory [29] and field trial [30]. By adding the bidirectional optical switch, the optical signals from left and right fibers in Fig. 2 can pass through the optical amplifier and be routed to the proper channels of fibers at the opposite sides. In spite of the simple architecture in Fig. 2, a cost effective implementation will be challenging.

A lightpath can span two or more fiber links, e.g., lightpath (g) in Fig. 1. Hence, the optical switches in the intermediate nodes must also support bidirectional transmissions. In principle, the optical switches built with micro-mirrors using micro electro mechanical systems (MEMS) technology are in nature bidirectional [37]–[39]. Although MEMS optical switches have the advantage of low crosstalk, low insertion loss, and up to a thousand input/output ports, its cost and reliability issues have encouraged other kinds of bidirectional optical switches to be proposed with technologies such as tunable fiber grating and/or arrayed waveguide grating (AWG) [31]–[35]. However, the scalability of such bidirectional optical switches at the moment is not as good as that of MEMS optical switches.

Lightpaths passing through the same fiber link must be assigned channels of different wavelengths regardless of the lightpath direction. Wavelength contention may therefore also occur when we set up new lightpaths in networks with reversible wavelength channels. Actually, it is necessary to solve the routing and wavelength assignment (RWA) problem as in normal WR networks except that lightpaths with opposite directions can pass through the same fiber link, e.g., lightpaths (a) and (b) in Fig. 1. Wavelength converters (WCs) can certainly be used to reduce the lightpath setup blocking probability caused by wavelength contentions. In normal WR networks, WCs can be added at either the inputs or outputs of the optical switch in a WR node. However, such approaches may not be applicable in this case because the WC must be transmission direction reconfigurable. A more feasible approach is as shown in Fig. 3, i.e., optical signals from both sides of the RW node can be wavelength converted by the shared-by-node WCs [4] before being switched to their preferred fiber links.

A WR node should be able to transmit/receive the local user data to/from the proper wavelength channels of the proper fibers. In Fig. 1, Node 3 can send local user data to channels ( $\lambda_1$  and  $\lambda_2$ ) on fiber connected to Port 1 and Channel  $\lambda_1$  on fiber connected to port 2 so that Node 1 can receive the data from those channels, i.e., the lightpaths (e), (f) and (g). As each wavelength channel can serve as input and output, the

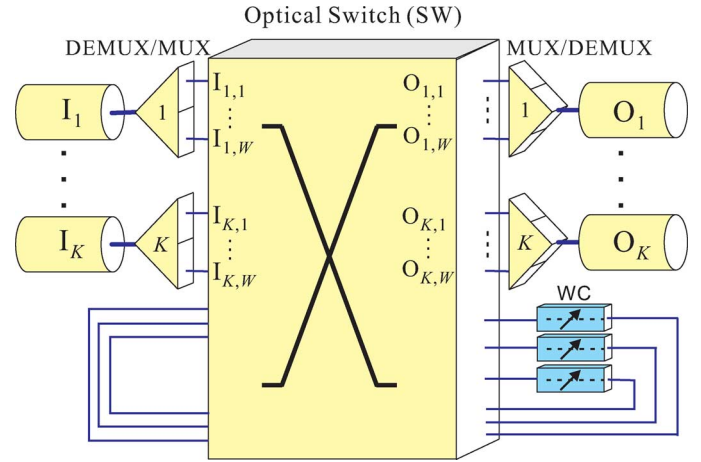


Fig. 3. A RW node with reversible wavelength channels and wavelength conversion capability.

bidirectional optical switches inside the nodes should be able to connect a user transmitter/receiver to any channel of any fiber connected to the node. It is preferred that the optical switches can provide per-node add-drop functionality [35]. Depending on implementation considerations, bidirectional add-drop multiplexers may also be first used on each port [18]–[21], e.g., Ports 1, 2, 3 and 4 in Fig. 1. Nevertheless, extra hardware is then needed to provide the per-node add-drop functionality.

The numbers of transmitters and receivers of a  $k$ -degree normal WR node with  $f$  fibers per link and  $w$  channels per fiber are  $kfw$  because they should be equal to the numbers of available output and input wavelength channels, e.g., there will be four transmitters and four receivers in each node of Fig. 1 for a normal WR network. As in the proposed system a node can configure all its available wavelength channels as either inputs or outputs, we can in principle install up to  $2kfw$  transmitters and receivers at a node to have the best system performance. However, the maximum utilization of transmitters and receivers will only be 50% in this case. In general, the numbers of transmitters and receivers of reversible wavelength channels can be equal to that of normal WR networks if the fluctuation of traffic distribution is not drastic. In Sections III and IV, we have demonstrated that significant performance improvement can be obtained with reversible wavelength channels even if only  $kfw$  transmitters and receivers per node are used.

The above discussions show that most of the required technologies for reversible wavelength channels are already available, and there is no foreseeable technology bottleneck. Reversible wavelength channels allow us to upgrade WR network by using additional devices rather than by installing new fiber infrastructures.

### B. Application Scenarios

At the moment, reversible wavelength channels are likely to be more suitable for access/metro networks because of the dynamic traffic characteristic and the less stringent optical signal power tolerance. As shown in Section III, reversible wavelength channels will provide significant improvement to the blocking performance even if the network traffics are statistically symmetric, i.e., on average the intensity of traffic from Node A to



Node B equals that from Node B to Node A. Obviously, reversible wavelength channels will add little gain if the traffic symmetry is deterministic, e.g., another connection must be set up from Node B to Node A simultaneously when a connection is set up from Node A to Node B. Also, networks with highly static traffic will not benefit from the flexibility of reversible wavelength channels. Therefore, wavelength reversible channels may not be attractive to current optical backbones because their traffics are highly aggregated on high capacity trunks. In contrast, recent study shows that the traffic characteristics of access/metro networks are rather dynamic and asymmetric [10].

Unlike systems with fixed channel direction [27]–[30], the optical signals in our proposed system need extra demultiplexing/multiplexing and switching processes when they are re-amplified (see the optical amplifier shown in Fig. 2) because of the direction configurability of each wavelength channel. The signal power loss caused by the extra processes may be up to 5 to 10 dB depending on the implementation details. It is preferable that the signal attenuation between nodes is not very large such that the quality of the optical signals is still above the minimum requirements after the additional processing. Otherwise, optical amplifiers with larger gain and higher output power will be needed to compensate for the extra signal power loss, i.e., longer erbium doped fiber, stronger pump laser, and multistage approach will have to be used for the EDFAs [40]–[42]. Apart from the extra cost incurred, physical layer issues such as optical signal to noise ratio (OSNR) will be a concern when using higher power optical amplifiers. Hence, networks with tight link budget and stringent OSNR requirement such as the optical backbones may need much effort to integrate the reversible wavelength channels into the system. On the other hand, all these issues are easier to handle in the access/metro networks.

Further complications will arise if Raman amplifiers [43], instead of EDFAs, are used to amplify the signals. Despite its many advantages, Raman amplification is polarization-dependent, i.e., Raman gain depends on the mutual orientation of the states of polarization of the pump and signal waves. As most optical fibers are slightly birefringent, typical Raman amplifiers will use the backward pumping scheme such that the polarizations of the Raman pump and the signal will be rapidly varying relative to each other. The Raman gain will then be effectively averaged. Thus, polarization-dependent gain such as that obtained with Raman amplifiers or optical parametric amplifiers poses a significant challenge to reversible wavelength channels. Bidirectional pumping, polarization scrambling, and polarization diversity can be used to alleviate the polarization dependence of the Raman gain at the expense of increase in hardware cost and system complexity. More work will be needed to study the use of polarization-dependent amplification scheme in reversible wavelength channels.

### III. PERFORMANCE EVALUATION

We first demonstrate the blocking performance of the proposed reversible wavelength channel approach on the 16-node ring network, the  $4 \times 4$  mesh network (Fig. 4), and the NSFNet topology network (Fig. 5) with the assumption that the total traffics in each direction of a pair of nodes are statistically

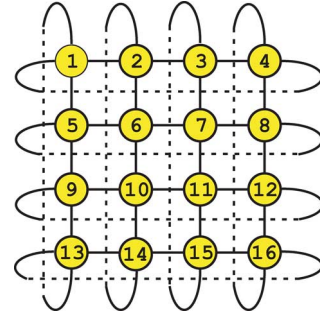


Fig. 4. The  $4 \times 4$  mesh network.

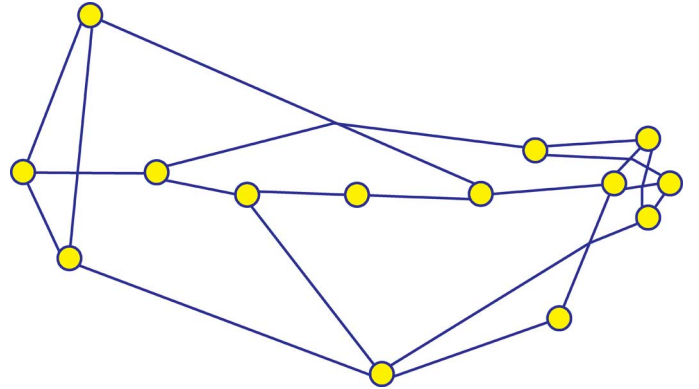


Fig. 5. The NSFNet (1991) network topology. The original map of the network is available from the Internet (<ftp://ftp.uu.net/inet/maps/nsfnet/>).

symmetric, i.e., the traffic from Node A to Node B will be on the average equal to that of Node B to Node A. We therefore will have a general concept of the performance of the reversible wavelength channel approach on regular topology (ring and mesh) and irregular topology (NSFNET) networks. In the simulations, two adjacent nodes of a network are connected by two links which have opposite transmission directions if the normal WR network approach is used. For the reversible wavelength channel approach being used, however, the transmission directions of all wavelength channels in the two links are reversible. There may be one, two, four, and eight fibers per link, depending on the simulation requirement. We assume that there are 32 wavelength channels per fiber. A user data transmission request arrives at the system as a Poisson process and chooses a random pair of source and destination nodes. Shortest path routing is used to set up the required lighthpath. After a lighthpath has been set up between the source and destination, the holding time of the lighthpath will be an exponential random number with a mean of one time unit. If there is no wavelength channel available on any link of the path, the data transmission request will be blocked. The numbers of transmitters and receivers in a  $k$ -degree normal WR node is  $kfw$  where  $f$  is number of fibers per link and  $w$  is the number of channels per fiber. We assume that there are also  $kfw$  transmitters and receivers in the  $k$ -degree node of the networks with reversible wavelength channels. We use the batched mean method (batch size of  $10^4$  time units) with discarding the first batch to compute the results. All simulations are run sufficiently long such that 95% confidence intervals are less than 1% of the results.

In normal WR networks, two lightpaths with the same end nodes but opposite directions will never have bandwidth and wavelength contentions with each other. It is because  $\text{path}(n_1, n_k) = \{n_1, n_2, \dots, n_k\}$  implies  $\text{path}(n_k, n_1) = \{n_k, n_{k-1}, \dots, n_1\}$  from shortest routing and fiber links with opposite directions are used to connect node pairs  $(n_x, n_y)$  and  $(n_y, n_x)$ . Hence, a normal WR network can be considered as two independent networks each of which has its own sets of lightpaths and fiber links if we partition the lightpaths and fiber links according to their transmission directions. Note that this observation may not be valid if the lightpath routing is not shortest path routing. With reversible wavelength channels, it is conceptually equal to combining the link capacities and traffic loadings of the two independent networks. Evidently, the lightpath setup blocking probability will be much smaller regardless of the traffic distributions since it is well-known that doubling a link capacity will improve the blocking performance even if the loading is also doubled [44]. Hence, the proposed reversible wavelength channel approach should also provide performance improvement in the symmetric traffic situations. To demonstrate the validity of the concept, we also plot the results of WR networks with double the link capacity and traffic loading in symmetric traffic situations. Their blocking probabilities should be very close to that of reversible wavelength channels.

Figs. 6–8 show the simulation results. The loading in the horizontal axis of the figures is a normalized value of  $(\text{number of transmission data requests in a time unit}) / (\text{number of nodes} \times \text{number of channels per fiber} \times \text{number of fibers per link} \times \text{minimum number of node degree in the network})$ . From this arrangement, we can directly compare the blocking performance of systems with different numbers of fibers per link in the same figure. To allow one to have a rough idea when comparing capacity against loadings, the maximum absolute per node loadings of all curves are also marked in the figures. In the figures, the curves with pluses, diamonds, crosses, and triangles are the blocking probabilities for normal WR networks with one, two, four and eight fibers per link, respectively, while the curves with circles and squares are for those using reversible wavelength channels on networks with one and four fiber per link. From the figures, we observe that significant blocking performance improvements have been obtained no matter of the network topology being ring, mesh and NSFNet. From Figs. 6–8, we observe that the blocking performance of WR networks with reversible wavelength channel is close to that of WR networks with double the link capacity and traffic loading, i.e., the curves with circles and squares are nearly overlapping the curves with diamonds and triangles. Hence, one can confirm that the reversible wavelength channel approach can provide nontrivial performance improvement for different network topologies and different number of fibers per link even if the traffic between any pair of nodes is symmetric.

For the blocking performance of the proposed reversible wavelength channel approach in the cases of asymmetric traffic, we only show the results for the NSFNet topology network since other results are similar. Figs. 9 and 10 show the simulation results for the cases of one and four fibers per link when the traffic between any pair of node is asymmetric. In the

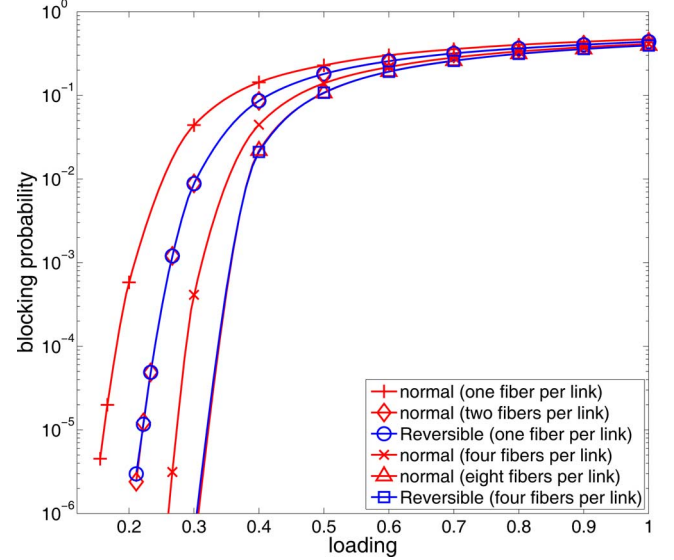


Fig. 6. Blocking performance of the proposed reversible wavelength channel approach on the 16-node ring network with symmetric total traffic. There are 32 wavelength channels per fiber. Maximum absolute per node loadings of the curves with pluses and circles: 32 erlangs, curves with diamonds: 64 erlangs, curves with crosses and squares: 128 erlangs, and curves with triangles: 256 erlangs.

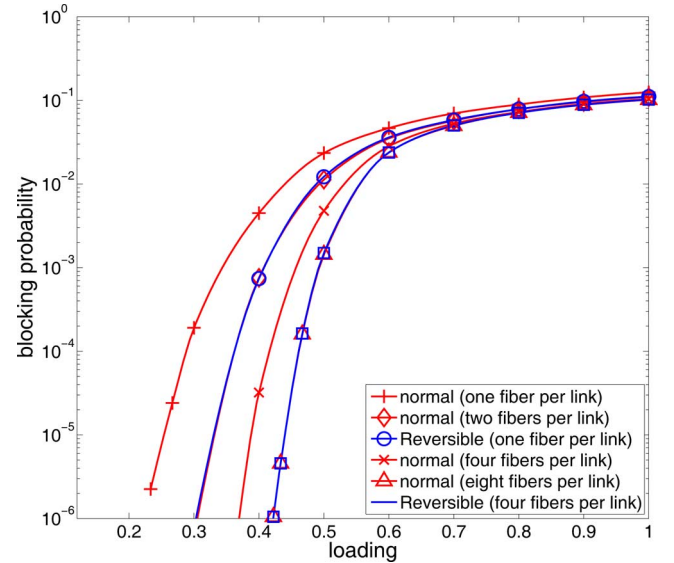


Fig. 7. Blocking performance of the proposed reversible wavelength channel approach on the  $4 \times 4$  mesh network with symmetric total traffic. Please refer to Fig. 6 for the traffic parameters.

simulations, we flip a biased coin when two nodes are chosen for the source and destination. According to the outcome of the flip, we may swap the source and destination assignment such that the total traffic from one transmission direction over that from another direction will be on the average equal to an asymmetry factor. For convenience, asymmetry factor is equal to or large than one. Surely, a network with symmetric traffic will have an asymmetry factor of one. A network with larger asymmetry factor means that the traffic between each pair of nodes becomes more asymmetric. In Figs. 9 and 10, the curves with triangles, asterisks, crosses, and pluses represent the results of normal WR networks with asymmetry factors

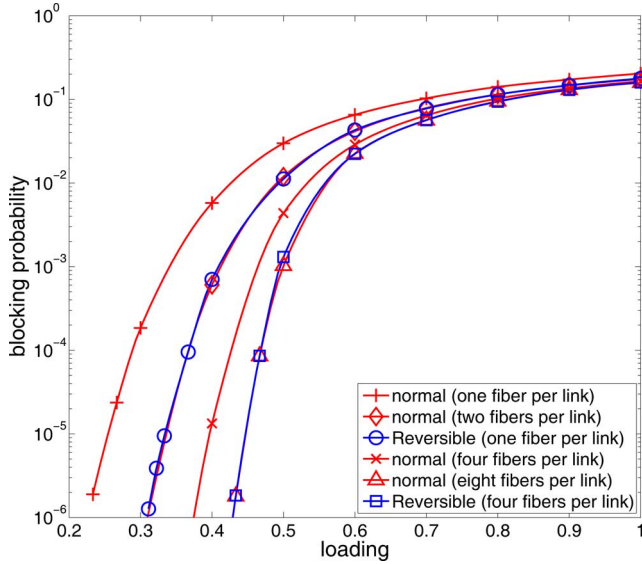


Fig. 8. Blocking performance of the proposed reversible wavelength channel approach on the NSFNet topology network with symmetric total traffic. Please refer to Fig. 6 for the traffic parameters.

of 1, 1.1, 2 and 10, respectively, while the curves with stars, squares, diamonds and circles are for those using reversible wavelength channels. From Figs. 9 and 10, one can observe that normal WR networks will suffer greatly when the system traffic becomes asymmetric. On the other hand, reversible wavelength channel WR networks will have similar blocking performance even if the asymmetry factor increases from 1 to 10. As we discussed in previous paragraphs, reversible wavelength channel approach is conceptually equal to combine the capacities and traffic loadings of the two links originally having opposite transmission directions in normal WR networks. Modifying the ratio of loading traffics on the opposite direction links will not change the blocking probability if the total traffic loading remains unchanged. This demonstrates the effectiveness of the reversible wavelength channel approach in handling the frequent changes of network traffic patterns that we may not have foreseen. Though the reversible wavelength channel approach requires many WR network devices to be upgraded, the investment will be future-proof.

#### IV. DISCUSSION OF OTHER IMPLEMENTATION APPROACHES

So far, we have assumed that all wavelength channels of all links in a WR network are reversible. From a practical point of view, this may be costly and not necessary in many occasions. For example, one may prefer to upgrade only some links of a network to have reversible wavelength channels. Clearly, it will be an interesting and complicated optimization problem to find out the proper locations and numbers of links to maximize the system performance with minimum hardware upgrade. Another implementation alternative is to use the reversible waveband approach. From Fig. 2, one may observe that the size of the optical switch in the bidirectional optical amplifier will grow with the number of wavelength channels. If the reversibility of transmission direction is waveband-based, waveband switches can be used to reduce the cost. Note that waveband reversibility is a compromise between performance and implementation cost.

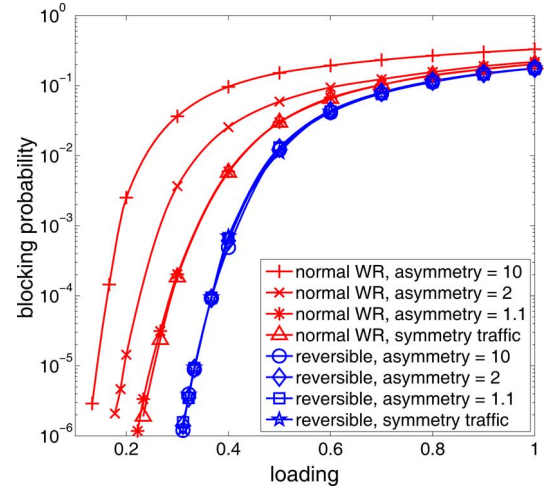


Fig. 9. Blocking performance of the proposed reversible wavelength channel approach on the NSFNet topology network with different asymmetry factors. There are 32 wavelength channels per fiber but only one fiber per link. The maximum absolute per node loadings of all curves are 32 erlangs.

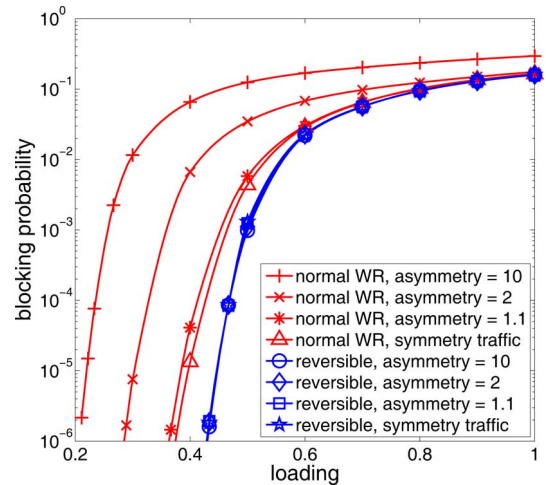


Fig. 10. Blocking performance of the proposed reversible wavelength channel approach on the NSFNet topology network with different asymmetry factors. There are 32 wavelength channels per fiber and four fibers per link. The maximum absolute per node loadings of all curves are 128 erlangs.

In some occasions, one may encounter a substantial reduction of reversibility gain.

Figs. 11 and 12 show the blocking performance of reversible waveband approach on the NSFNet topology network with one and four fibers per link using different waveband sizes. The 32 wavelength channels in a fiber are grouped into equal size wavebands. Hence, there will be 4, 8, and 16 wavebands in a fiber if the waveband sizes are 8, 4, and 2. The transmission direction of a waveband is freely configurable if all wavelength channels in the waveband are not occupied. Since waveband switches are used in bidirectional optical amplifiers, however, the transmission direction of the waveband will be fixed once any waveband has been used for transmission. Consequently, the set up of lightpath will become more complicated because we have to consider the transmission direction of the waveband that an idle wavelength channel belongs to. Also, we should prefer to use wavebands already having channels in



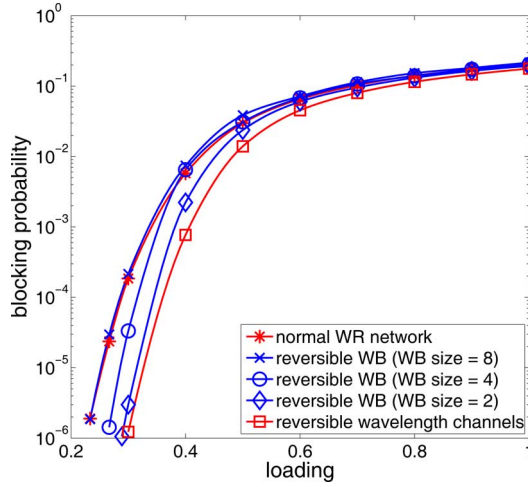


Fig. 11. Blocking performance of the reversible waveband approach on the NSFNet topology network with symmetric total traffic. There are 32 wavelength channels per fiber but only one fiber per link. The maximum absolute per node loadings of all curves are 32 erlangs.

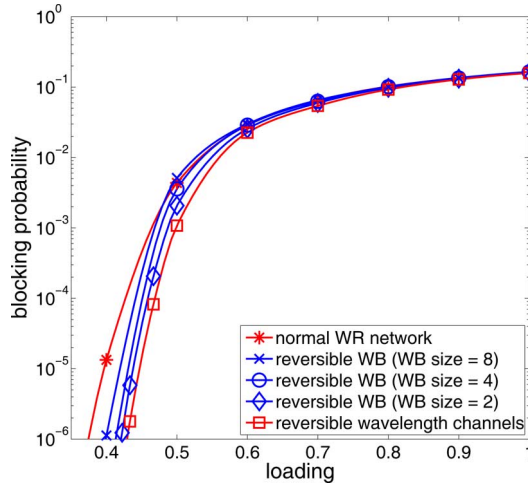


Fig. 12. Blocking performance of the reversible waveband approach on the NSFNet topology network with symmetric total traffic. There are 32 wavelength channels per fiber and four fibers per link. The maximum absolute per node loadings of all curves are 128 erlangs.

transmission when setting up a lightpath. This is to maximize the number of free wavebands, and to have more flexibility in setting up additional lightpaths afterward.

In Figs. 11 and 12, the curves with diamonds, circles, and crosses are blocking probabilities of the reversible waveband approach using waveband sizes of 2, 4, and 8, respectively. For reference, blocking probabilities of normal WR network and the reversible wavelength channel approach are plotted as the curves with asterisks and squares, respectively. From Figs. 11 and 12, we observe that the reversible waveband approach with large waveband size will not always have better blocking performance than normal WR network. For example, the curve with crosses is above the curve with asterisks in Fig. 11. The reversible waveband approach will have blocking performance close to that of the reversible wavelength channel approach only if the waveband sizes are small enough, e.g., waveband sizes

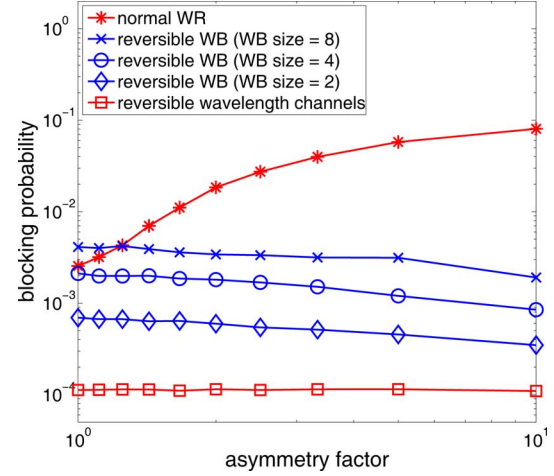


Fig. 13. Blocking performance of reversible waveband approach on NSFNet topology network with different asymmetry factors. There are 32 wavelength channels per fiber but only one fiber per link. The maximum absolute per node loadings of all curves are 32 erlangs.

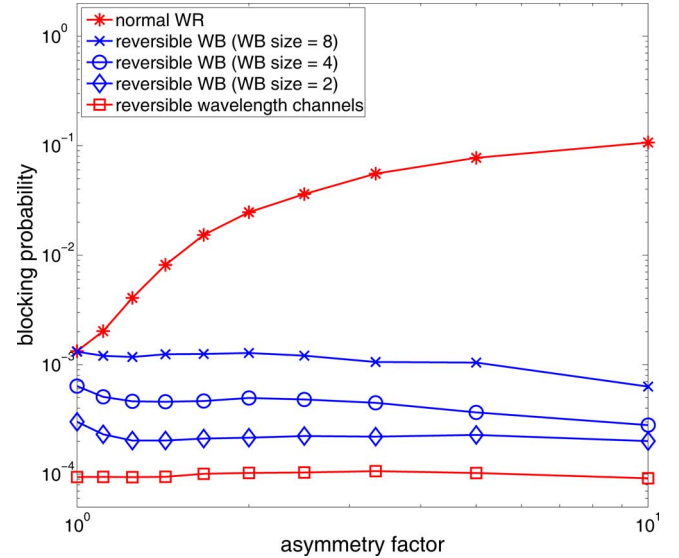


Fig. 14. Blocking performance of reversible waveband approach on NSFNet topology network with different asymmetry factors. There are 32 wavelength channels per fiber and four fibers per link. The maximum absolute per node loadings of all curves are 128 erlangs.

$\leq 4$ . Hence, one have to balance the tradeoff between performance and implementation cost if the reversible waveband approach is used.

A nice feature of the reversible waveband approach is that its performance is also insensitive to asymmetric traffic. Figs. 13 and 14 are the blocking performance of the reversible waveband approach in the NSFNet topology network with one and four fibers per link. The normalized loadings are set to 0.37 and 0.43 in the two networks such that the reversible wavelength channel approach will have blocking probability about  $10^{-4}$ . From the figures, we observe that the blocking performance of normal WR network degrades quickly with the increase of asymmetry factor while that of the reversible wavelength channel approach basically remains unchanged in the whole range of the asymmetry factor. On the other hand, the blocking probability of the



reversible waveband approach decreases slightly when asymmetry factor increases from 1 to 10. This is because large asymmetry factor implies the traffic from any pair of nodes becomes more ‘unidirectional’. New lightpaths are easier to find channels available in wavebands with the required transmission direction. Hence, the bandwidth utilization of a waveband will be improved when the asymmetry factor is large.

Note that the blocking performance of the reversible waveband approach can be further improved with other methods such as non-uniform waveband size. For example, we find that the reversible waveband approach with non-uniform waveband size of  $\{2, 2, 2, 2, 4, 4, 8, 8\}$  will have better performance than that of uniform waveband size of 4. Nevertheless, it will become another interesting optimization problem when the number of wavelength channels is large.

## V. CONCLUSION

We observe that in the real world traffics between users are often asymmetric and network traffic patterns change frequently. More flexible bandwidth utilization is desired. We therefore propose reversible wavelength channels to be used in wavelength-routed (WR) networks. Reversible lanes in highway systems have already been widely regarded as of one of the most cost-effective methods to provide additional capacity for periodic unbalanced directional traffic demand while minimizing the total number of lanes on a roadway. However, reversible wavelength channels so far have not been discussed in WR networks even though we observe that most of the required technologies are already available. In this paper, we discuss all the required technologies for implementing reversible wavelength channels in WR networks. We demonstrate that the reversible wavelength channel approach can provide significant performance improvement for WR networks when the traffic is asymmetric. Even if the traffic is symmetric, we also have nontrivial performance improvement with the reversible wavelength channel approach, i.e., the blocking performance of WR networks with reversible wavelength channels will be similar to that of normal WR networks with doubling the number of fibers per link. Different implementation approaches for reversible wavelength channels are discussed. Among them, the performance of the reversible waveband approach is discussed in detail.

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